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TECHNICAL NOTE

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SIMULATOR STUDIES OF SIMPLE ATTITUDE CONTROL

FOR SPIN-STABILIZED VEHICLES

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SUMMARY

A simple attitude-control system which used body-mounted attitude-error sensors and a single body-mounted reaction-control jet was devised to provide a reliable lightweight attitude control for the final stage of small research spin-stabilized vehicles. The simulated systems utilized the spin of the vehicle to provide attitude-sensor scan, signal phasing, and control-torque commutation. Results of the simulation for three systems - horizontal or orbit injection, vertical probe, and angle-of-attack control - for reentry vehicles showed satisfactory performance over a sizable range of parameter variation.

INTRODUCTION

Spin stabilization is currently used as an open-loop system to maintain a constant missile attitude in space coordinates. Such a system suffers from the fact that attitude errors occur because of torques applied to the body by wind shear, tipoff, thrust-misalinement transients, and so forth. The system described herein for a spinning body provides a closed-loop attitude-control system which will correct any attitude errors and damp out the coning produced by such torques.

The system described is extremely simple and has only two moving parts: a rate gyro or angular accelerometer for damping, and a solenoid valve for the reaction jet. The electronic circuitry, employed in the simulation studies described herein, used a total of six transistors and two vacuum tubes. In addition, the system would use either body-fixed attitude or angle-of-attack sensors, whose scan is provided by the spin of the vehicle. The use of absolute-attitude sensors such as horizon scanners makes it necessary to control only the final stage of multistage vehicles, and thus the control systems for the previous stages may possibly be eliminated. Elimination of these control systems appears feasible even in such a critical case as orbit injection because of the large percentage of final velocity normally supplied by the final stage.

The control system is fail safe, in that any component failure cannot cause large deviations of the missile flight path. A component failure resulting in a hard-over command results in no more disturbance than a thrust misalinement, the effect of which is limited by the spin of the vehicle.

The simulations described herein represent three specific missile configurations. The horizontal, or orbit-injection, system controls the final stage and the empty case of the previous stage, and it allows the final stage to be fired without the control system for minimum weight in the final stage. This system, of course, will not correct for torques applied to the final stage after separation. In the case of the vertical probe, the entire control system is contained in the final stage. The angle-of-attack system represents vehicle and trajectory parameters encountered in the flight of a reentry-research-program vehicle.

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SYMBOLS

I_X	spin inertia
I_Y	pitch inertia
I_Z	yaw inertia
M_X	moment about spin axis
M_Y	moment about pitch axis
M_Z	moment about yaw axis
$M_{Z,c}$	control torque
p	spin rate
q	pitch rate
r	yaw rate
X,Y,Z	space-fixed coordinate system
θ	pitch angle, space coordinate

ϕ spin angle, space coordinate

ψ yaw angle, space coordinate

A dot over a symbol represents a first derivative with respect to time.

DESCRIPTION OF CONTROL SYSTEM

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Four general functions are required of the control system: error sensing, vehicle damping, control logic, and vehicle torquing. Since a spinning vehicle exhibits properties similar to those of a free gyroscope, it must be torqued about a space axis perpendicular to the spin axis and also perpendicular to the axis about which the corrective maneuver is desired. Control torques may be applied by means of a single reaction jet perpendicular to the spin axis of the vehicle and positioned as far from the center of gravity as practicable. (See fig. 1.) This jet is activated only during that portion of the spin revolution when it is pointed in a direction to produce torque about the desired space axis.

Error Sensing

In order to utilize a single body-mounted reaction jet for control about two axes, the system must not only detect attitude errors but must also convert the resulting error signals into properly phased command signals to the reaction jet. Both the detecting and the phasing functions are performed by body-mounted error detectors. Although various types of attitude-error detectors may be adapted to this system, only horizon scanners and angle-of-attack sensors will be discussed.

Figure 1 illustrates the application of a horizon-scanner attitude-error detector to control a vehicle's spin axis parallel to the local horizontal. In this case the scanner consists of a pair of body-mounted telescopes of narrow fields of view. These telescopes are so oriented in the vehicle that when the vehicle is at the proper altitude, with its spin axis horizontal, the field of view of each telescope barely intersects the horizon as the vehicle spins. A radiation detector is located at the focal point of each telescope so that a signal pulse is produced as long as the telescope "sees" the horizon. These pulses are amplified and processed by suitable electronic circuitry to energize the reaction jet during the time that either telescope sees the horizon. If a small nosedown error in attitude exists, telescope A sees the horizon and commands a brief pulse of thrust from the jet each time the vehicle reaches the approximate roll attitude shown in figure 1; during this time telescope B does not see the horizon. These pulses of thrust produce a torque about the Z-axis which results in a precession of the vehicle about the Y-axis in a direction to reduce the error. Similarly, a noseup error is corrected by the same jet when commands are received from telescope B. The conical scan and circular appearance of the earth cause the time duration of the error pulses and, as a result, the average value of the corrective torque to be approximately proportional to the magnitude of the pitch error for small error angles. Errors in azimuth may be corrected by the same reaction jet when error signals are introduced from a suitable azimuth reference such as a sun scanner.

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Adjustment of the mounting angles of the scanner telescopes allows the vehicle spin axis to be stabilized at small angles above or below the local horizon, but a different error-sensing arrangement is required if the spin axis must be stabilized vertically. Figure 2 shows how this may be accomplished with the use of a single wide-angle telescope, positioned to see the horizon during the entire spin revolution of the vehicle when the spin axis is vertical. The output of the scanner telescope is proportional to the percentage of its field of view occupied by the earth, so that error in verticality of the vehicle results in an approximately sinusoidal output from the scanner. This signal is employed to turn on the reaction jet during the positive half-cycle of the error signal and off during the negative half-cycle. Because of the angular relation of the scanner to the reaction jet, the resulting average torque is in the proper direction to precess the vehicle back to a vertical attitude. It will be noted that near the control point the duty cycle of the jet in this case is approximately 50 percent. This 50-percent duty cycle allows the addition of a second jet which has a thrust direction diametrically opposite to that of the first and which is energized only when the first jet is deenergized. This arrangement not only results in a somewhat faster system response, but it is also readily adaptable to a constant-mass-flow solid-propellant gas generator.

An angle-of-attack sensor may be substituted for the scanner telescope in the system just described to insure a zero-lift trajectory for a vehicle operating in the atmosphere. Such an arrangement is shown in figure 3.

Vehicle Damping

Artificial vehicle damping is required for stable operation of the control systems described. Because of the interchange of energy in the spinning vehicle between the axes perpendicular to the spin axis, the damping applied about one of these axes is sufficient to damp the entire system. A single rate gyro or angular accelerometer controlling a single on-off reaction jet was found to provide adequate damping. By employing suitable control logic, the same reaction jet can be used for both attitude control and vehicle damping. The rate gyro must be so oriented as to measure angular rates about the torqued axis of the vehicle; the angular accelerometer must be oriented to measure accelerations about the same axis that the attitude errors are measured about.

Control Logic

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Signals from the attitude-sensing scanners and from the rate gyro may be combined in a number of different ways to generate a command signal to the control jet. Block diagrams of the circuits found from computer studies to give best results in the horizontal and the vertical systems are shown in figures 4 and 5, respectively. High-pass filters with a cutoff frequency below the spin frequency of the vehicle are inserted in the signal circuits from both scanners and rate gyros to block variations in zero signal level due to variations in ambient-radiation levels in the case of the scanners and due to possible misalinement of the sensitive axis in the case of the rate gyro. The components marked "switch" are devices which turn full on when a predetermined input-signal level is exceeded. In the horizontal system (fig. 4), the attitude and rate signals are converted to on-off signals by switches before being combined by the "Or" gate which allows an on signal from either source to actuate the control jet. In the vertical system (fig. 5), both signals are retained in analog or proportional form until they are summed. The signal limiter in the scanner circuit improves response to large transients and allows wide variations in scanner gain.

Vehicle Torquing

As mentioned earlier, the control jet is activated only during the portion of the vehicle roll cycle in which it is in such a position as to correct the attitude error. The timing of the pulse is accomplished by the relative positions of the attitude-error detectors and the control jet about the spin axis of the vehicle. Although only a control jet is discussed in this paper, it would also be possible to use other torquing means such as magnetic coils or reaction wheels to produce the control torque.

DESCRIPTION OF SIMULATION

Figure 6 presents a block diagram of the analog simulation of the control loop of the vehicle. The spinning-body-dynamics section is a mechanization of Euler's dynamical equations of a rigid body (ref. 1):

$$M_X = I_X\dot{p} - \left(I_Y - I_Z\right)rq \tag{1}$$

$$M_Y = I_Y\dot{q} - \left(I_Z - I_X\right)pr \tag{2}$$

$$M_Z = I_Z\dot{r} - \left(I_X - I_Y\right)pq \tag{3}$$

In the mechanization of these equations, the body is assumed to be symmetrical so that $I_Y = I_Z$, the rolling velocity p is assumed to be constant, and the damping is assumed to be zero. With these conditions, equation (1) is eliminated. The outputs of this section are then referred from the spinning-body-axis system to a space-axis system (ref. 2):

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$$\dot{\theta} = q \cos \phi - r \sin \phi \tag{4}$$

$$\dot{\psi} = \frac{1}{\cos \theta}(q \sin \phi + r \cos \phi) \tag{5}$$

$$\dot{\phi} = p + \sin \theta \tag{6}$$

For simplification, small angles are assumed and equations (5) and (6) are reduced to

$$\dot{\psi} = q \sin \phi + r \cos \phi \tag{7}$$

$$\dot{\phi} = p \tag{8}$$

respectively.

This transformation is accomplished by feeding spin and pitch rates from the body-dynamics section into a resolver which is rotated continuously at the spin rate of the vehicle. The resulting angular rates in the space-axis system are integrated to provide the space angles which represent the pointing direction of the spin axis.

The signal from the resolver that converts coordinates from space axes to body axes is fed through the error-signal-shaping circuitry, the output of which represents the signal from the position transducer, and is fed to the control electronic circuitry. This unit is a breadboard model of actual control circuits to provide the actual nonlinear parameters such as dead zone and hysteresis which would be encountered in a flight system. Also fed into the electronic unit is a signal from the spinning-body-dynamics section which represents rate about a body axis perpendicular to the position transducer. This body-rate signal is suitably modified by simulated rate-gyro dynamics before going to the control electronic circuitry as the rate-gyro signal. The electronic breadboard operates a solenoid valve, which in turn operates a switch to provide an input to the spinning-body-dynamics section to simulate torque produced by the reaction jet. Thus the vehicle control loop is completed.

In the case of the angle-of-attack control, the static margin of the vehicle is varied over a range of values, both positive and negative, which includes all values expected for the conditions under consideration. The aerodynamic moment is obtained by taking the signals directly from the space-to-body-axes resolver and feeding the signals back to the appropriate inputs in the spinning-body-dynamics section, as shown by the dotted lines in figure 6. In this case also the effect of aerodynamic damping is neglected.

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Procedures and Special Considerations

Table I lists the test conditions for the horizontal, vertical, and angle-of-attack control systems.

Horizontal control system.- The dynamics of the loaded final stage of a multistage vehicle coupled to the empty prior stage was set up for horizontal control with the nominal spin rate of 2.5 rps. Runs were made to demonstrate the feasibility of the analog signal-mixing scheme, and then the on-off signal-mixing scheme was programed. The problem was run several times to select the values for rate-switch operation and thrust level that would give the most satisfactory operation of the system.

The effects of spin rates which differed from design values were investigated, as well as differences in rate-switch threshold. A two-step rate-switch system was investigated which operated with a high rate threshold for the initial portion of the flight and changed to a low rate threshold for the final portion of the controlled flight. The rate-switch threshold was changed on a time basis. Also investigated were the effects of an unregulated reaction gas supply providing a reaction-jet thrust which varied inversely with the amount of gas used, and the addition of an azimuth control such as that derived from a sun seeker.

Vertical control system.- The dynamics of the loaded final stage were set up, and the spin rate was set at the nominal value of 2.5 rps. Runs were made to determine the most satisfactory rate and attitude gains. Both a single-jet system and a two-jet system were investigated. A constant-thrust jet was used to simulate operation of a solid-propellant gas generator. The effects of spin rates other than the design value, and of transducer-gain variations, were then studied.

Angle-of-attack control system.- The requirements for the angle-of-attack runs were set by a specific missile and trajectory used in a reentry research program and as such have some unusual aspects. The control system was required to begin functioning 10 seconds prior to burnout of the final-stage motor and to operate through the remainder of the motor burning and at least 20 seconds after burnout. The variations of the moments of inertia, therefore, were rather large throughout the flight. In addition, the dynamic pressure varied considerably throughout the flight (see table I) because of changing velocity and altitude, and the static margin varied because of the changing propellant-grain weight and the effect of the rocket exhaust plume on the flow separation on the afterbody.

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The requirements were approximated as follows. The total run time of 30 seconds was broken up into three parts. During the initial 10 seconds, a constant high value was assumed for the moments of inertia, corresponding to the partially burned motor, a constant high value was assumed for the dynamic pressure, and a constant high value was assumed for the gain of the angle-of-attack transducer whose sensitivity was proportional to the dynamic pressure. During the intermediate 10 seconds of the run, low moments of inertia were used to correspond to the final stage with the motor burned out, and constant intermediate values were used for the dynamic pressure and the gain of the angle-of-attack transducer. For the final 10 seconds of run the moments of inertia remained the same as for the intermediate 10 seconds, but a constant low value of dynamic pressure with the corresponding gain reduction on the angle-of-attack transducer was assumed.

After the initial 10-second run was made, the computer was switched to the "hold" condition to establish the initial conditions for the next portion of the run. The parameter changes were then made, and the computer was switched to "operate" for the intermediate 10 seconds. The computer was again switched to the hold condition, the parameters were changed to the final values, and the run was completed.

Initial runs were made to select suitable values of rate and angle-of-attack gain and jet thrust. The effects of variations in spin rate and in angle-of-attack transducer gain were studied. The relative merits of an unregulated stored-gas supply as opposed to a solid-propellant gas generator for control jet force were also studied.

RESULTS AND DISCUSSION

Horizontal Control System

Although the analog signal-mixing scheme provided satisfactory results with respect to response time and steady-state error, it was decided that the simplicity and insensitivity to gain variations afforded by an on-off signal-mixing system warranted study. Accordingly, this system was set up and found to perform as well as the analog mixing scheme. Typical computer runs of this system are shown in figure 7.

Since the horizontal system utilizes a control jet which operates over only a small portion of the missile rotation, a constant-mass-flow gas supply such as that provided by a solid-propellant gas generator could not readily be used. The stored-gas system programed into the computer consisted of a 2-cubic-foot container of gas at 3,000 lb/sq in. that operated a control jet directly from the supply pressure. Thus the jet force decreased proportionally with gas used.

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It was found that a jet designed to produce 150 pounds of thrust at a supply pressure of 3,000 lb/sq in. was adequate to bring the system to steady-state conditions from an initial error of 30°, with the nominal spin rate of 2.5 rps and a rate switch which operates at 2 deg/sec. However, at the higher spin rate of 3 rps, the supply pressure of the gas went to zero while an error of several degrees still remained. In order to alleviate this problem, a rate-switch threshold setting of 10 deg/sec was used, which allowed the system to reach steady state before the gas supply was exhausted. Here, however, an oscillation of about $\pm\frac{1}{2}^{\circ}$ remained in the steady-state condition.

A two-rate system was programed in which the rate switch was set for 15 deg/sec for the first 90 seconds of operation, and then switched to 1 deg/sec for the steady-state condition. This system returned the vehicle from the initial error point of 30° to steady-state conditions well within the 90 seconds for all spin rates, and had enough gas remaining to damp out the oscillations when the rate-switch setting was changed to 1 deg/sec.

When correcting for the large elevation errors, the system reached steady-state conditions with an azimuth error of several degrees. A signal from a simulated body-mounted sun scanner was added to the same electronic circuitry and control jet to provide an azimuth signal. The effects of various positions of the sun relative to the horizontal plane were investigated, and it was found that for the same two-rate control and gas supply outlined previously, the system operated satisfactorily at sun elevation angles up to approximately 45°.

The system settled upon consisted of a 2-cubic-foot supply of gas at 3,000 lb/sq in., a jet with initial thrust of 150 pounds, a dual-rate switch of 15 deg/sec and 1 deg/sec, and a sun-scanner azimuth reference. The steady-state error of this system was in all cases less than $\pm 1/2^{\circ}$, and the system reached steady-state conditions from an initial error of 30° in less than 100 seconds. This system would appear to be adequate in accuracy and response for injection control of a satellite from a vehicle such as Scout.

Vertical Control System

The vertical system was programed and rate and position gains and jet thrust at the nominal spin rate were selected. The ratio of the signals representing vehicle rate and attitude was 5.33 deg/sec per degree for the best system operation; the jet thrust was 5 pounds. Typical results are shown in figure 8. On-off signal-mixing techniques were tried for this system, but it was found that the system could not be stabilized in this mode.

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The system was programed to use the two-jet continuous-mass-flow techniques discussed earlier. Physically, this system would be much lighter and smaller than the single-jet system, and, as would be expected, it cut the time to reach steady state from an initial condition in half. The effects of spin rate and sensor-gain variations were then studied. Limiting the attitude signal to $\pm 2^\circ$ was found to improve the system dynamics. Variations in transducer gain of five times did not significantly affect the operation of the system, although the change could be seen in the steady-state oscillation and also, to a small extent, in the time of response of the system. The effect of spin-rate variation between 2 and 3 rps was somewhat more pronounced than that of transducer-gain variation, high rates resulting in sluggish transient response and low rates in erratic steady-state performance.

The system which appeared to be the best consisted of rate and attitude signals mixed in analog manner at a gain ratio of 5.33 deg/sec/deg, with the attitude-error signal limited at $\pm 2^\circ$, and a two-jet reaction-control system using 5-pound-thrust jets. The time required for this system to reach steady-state conditions from an initial error of 30° was less than 20 seconds for all values of spin rate and mixing gain investigated. The steady-state oscillation of the system was in all cases less than $\pm 1/2^\circ$.

Angle-of-Attack Control System

The dynamics of the angle-of-attack system were set up as described in the section "Procedures and Special Considerations" and the rate and angle-of-attack gains and the jet thrust were selected. The on-off signal-mixing scheme was investigated and again found to be unstable.

The three-part runs described in the preceding section were then made for various values of spin rate and for various amounts of aerodynamic-stability torques. These torques represent the range anticipated on the flight model under consideration and include cases in which the model has a negative aerodynamic static margin. Typical results are shown in figure 9.

A stored-gas system with the largest volume that could be accepted by the payload was investigated and was found to be inadequate. While it reduced an initial error of 3° to zero, the gas supply was exhausted at the end of 14 seconds. Accordingly, the solid-fuel gas-generator system with two jets was investigated and was found to work well.

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The most satisfactory system had a pair of 5-pound-thrust jets and a signal-mixing ratio of 20 deg/sec/deg with the attitude-error signal limited at $\pm 1^{\circ}$. This system will reduce an initial error of 3° to steady state in less than 8 seconds and an initial error of 15° to steady state in 14 seconds. Steady-state oscillation is less than $1/4^{\circ}$ in all cases.

CONCLUDING REMARKS

A system comprising a single body-mounted reaction-control jet and a body-mounted attitude-error sensor has been devised for attitude control of spin-stabilized vehicles, and analog-computer studies of the system have been made. Three general systems - horizontal or orbit injection, vertical probe, and angle-of-attack control - for reentry vehicles were studied and found to operate satisfactorily. Reasonable variations of spin velocity and control gains did not significantly impair the performance of the system. Adequate system damping was obtained from a single rate gyro or angular accelerometer.

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National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 14, 1962.

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TABLE I.- TEST CONDITIONS

	Horizontal system	Vertical system	Angle-of-attack system
Aerodynamic moment, ft-lb/deg	0	0	24 to -6
Aerodynamic damping	0	0	0
Moment of inertia, slug-ft^2:			
Transverse	871	34.15	200 to 70
Longitudinal	28	5.20	14.3 to 5.0
Spin rate, rps:			
Nominal	2.5	2.5	2.5
Range	2.0 to 3.0	2.0 to 3.0	2.0 to 3.0
Control jet:			
Thrust, lb	150 initial (varies with gas used)	6 (constant)	5 (constant)
Moment arm, in.	100	48	60 to 66
Rate-gyro characteristics:			
Natural frequency, cps	10	10	10
Relative damping, percent of critical	10	10	10
Attitude-sensor characteristics	Zero field of view	Linear output limited at $\pm 2^\circ$	Linear output limited at $\pm 1^\circ$ for dynamic pressure of 200 lb/sq ft
Valve time lag, msec	20	20	20
Hysteresis, deg	Not simulated	0.01	0.01
Hysteresis, deg/sec	Not simulated	0.26	0.26
Dynamic pressure, lb/sq ft	0	0	200 to 75

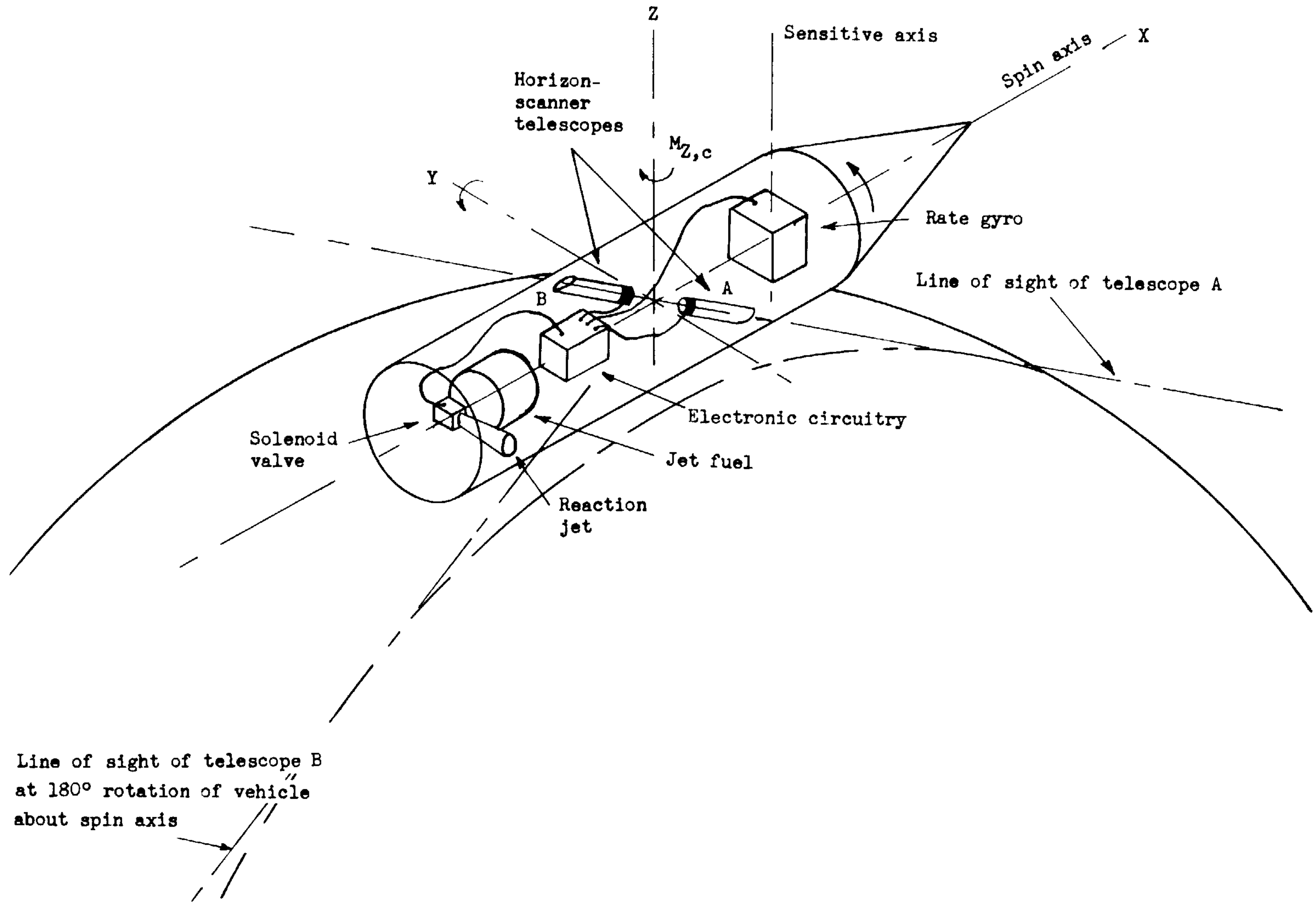

Figure 1.- Horizontal-control system.

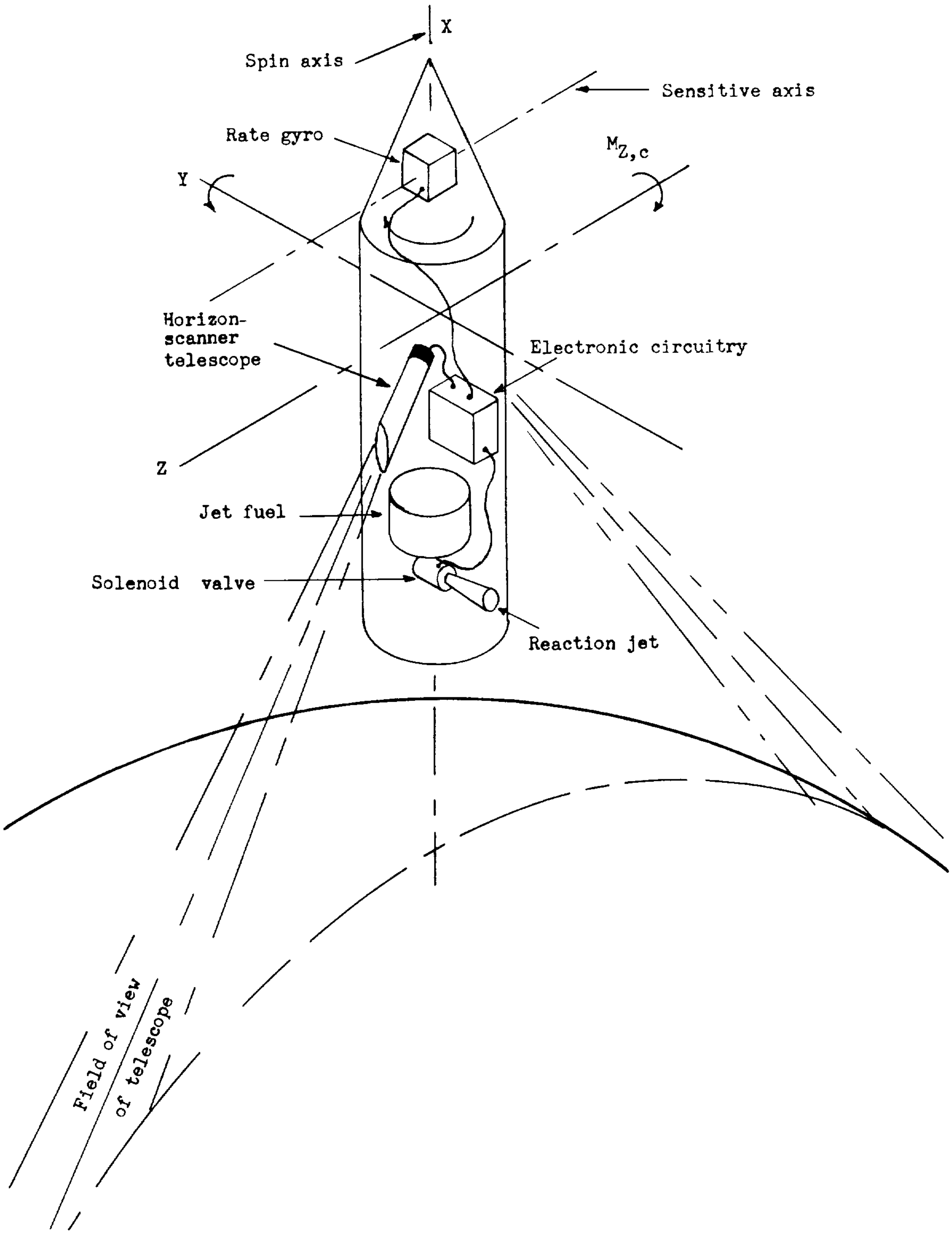

Figure 2.- Vertical-control system.

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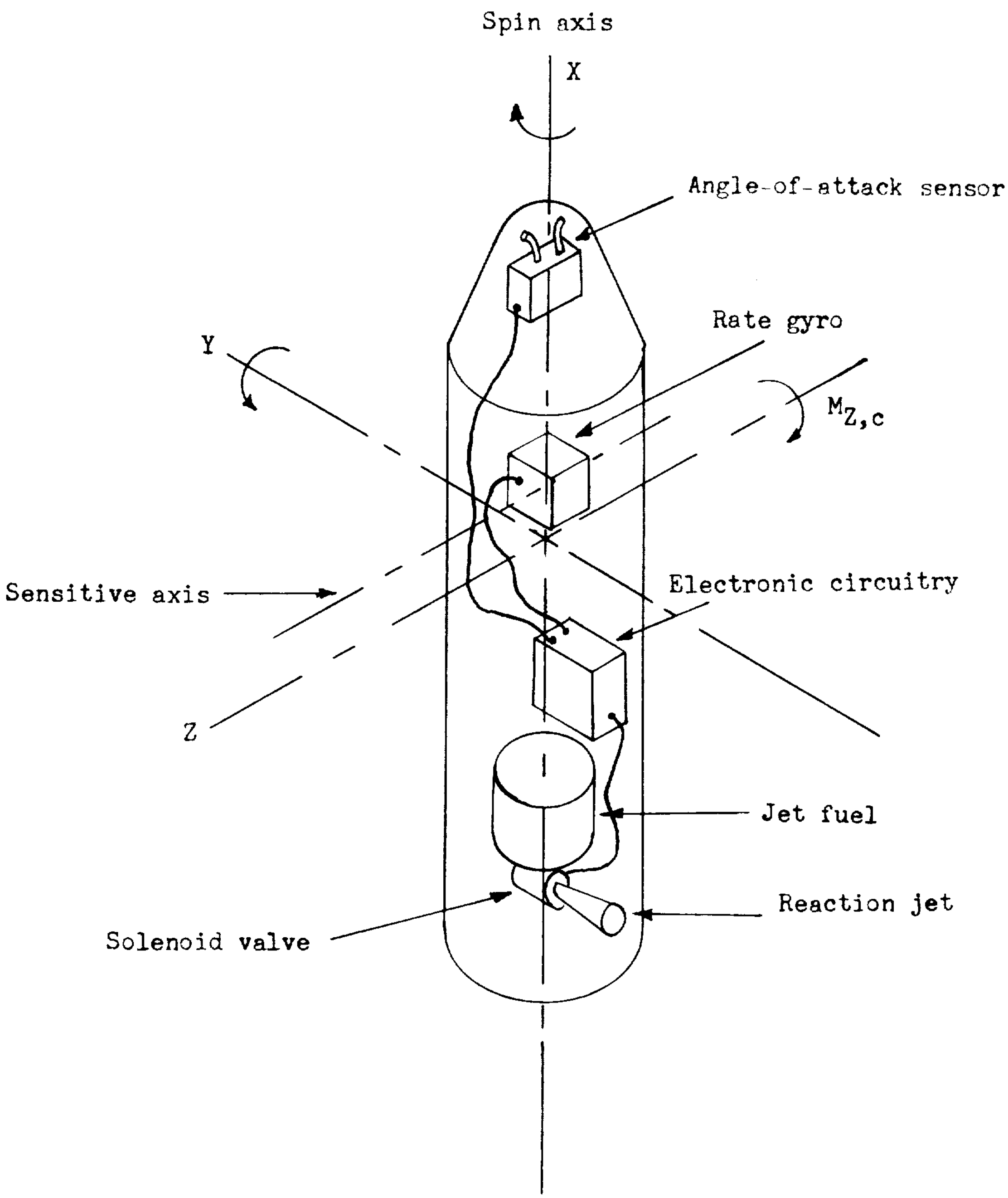

Figure 3.- Angle-of-attack system.

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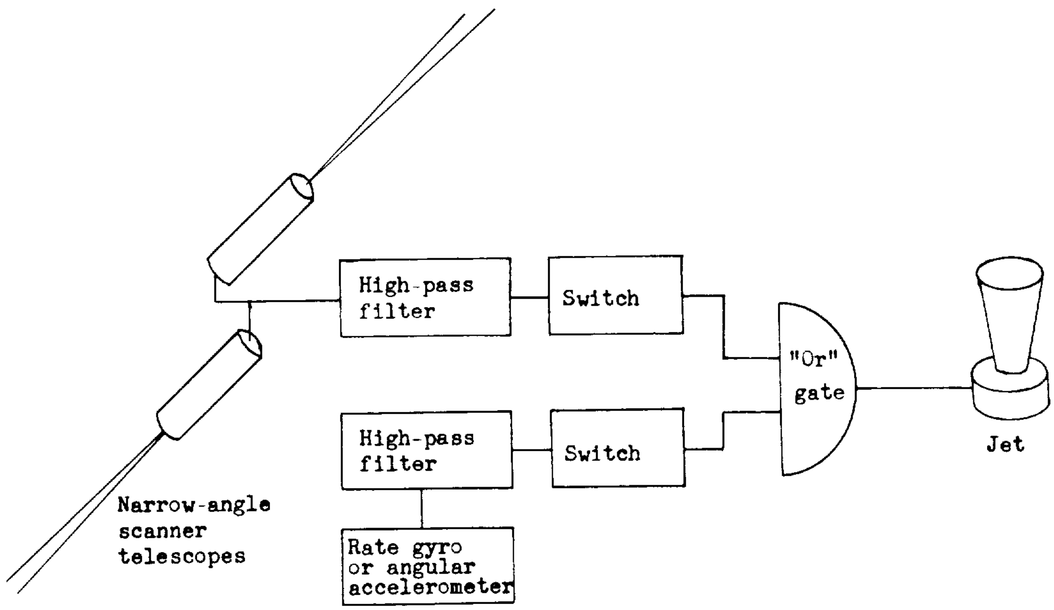

Figure 4.- Horizontal-control block diagram.

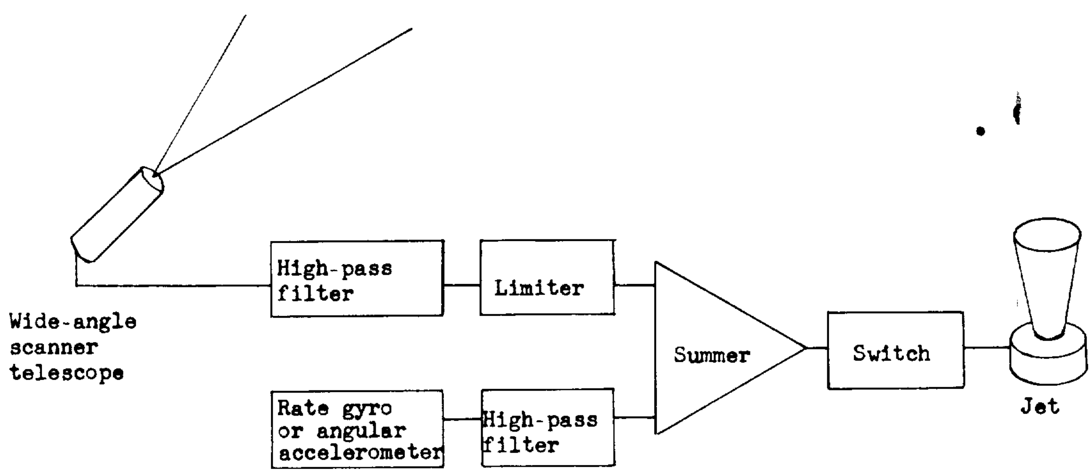

Figure 5.- Vertical-control block diagram.

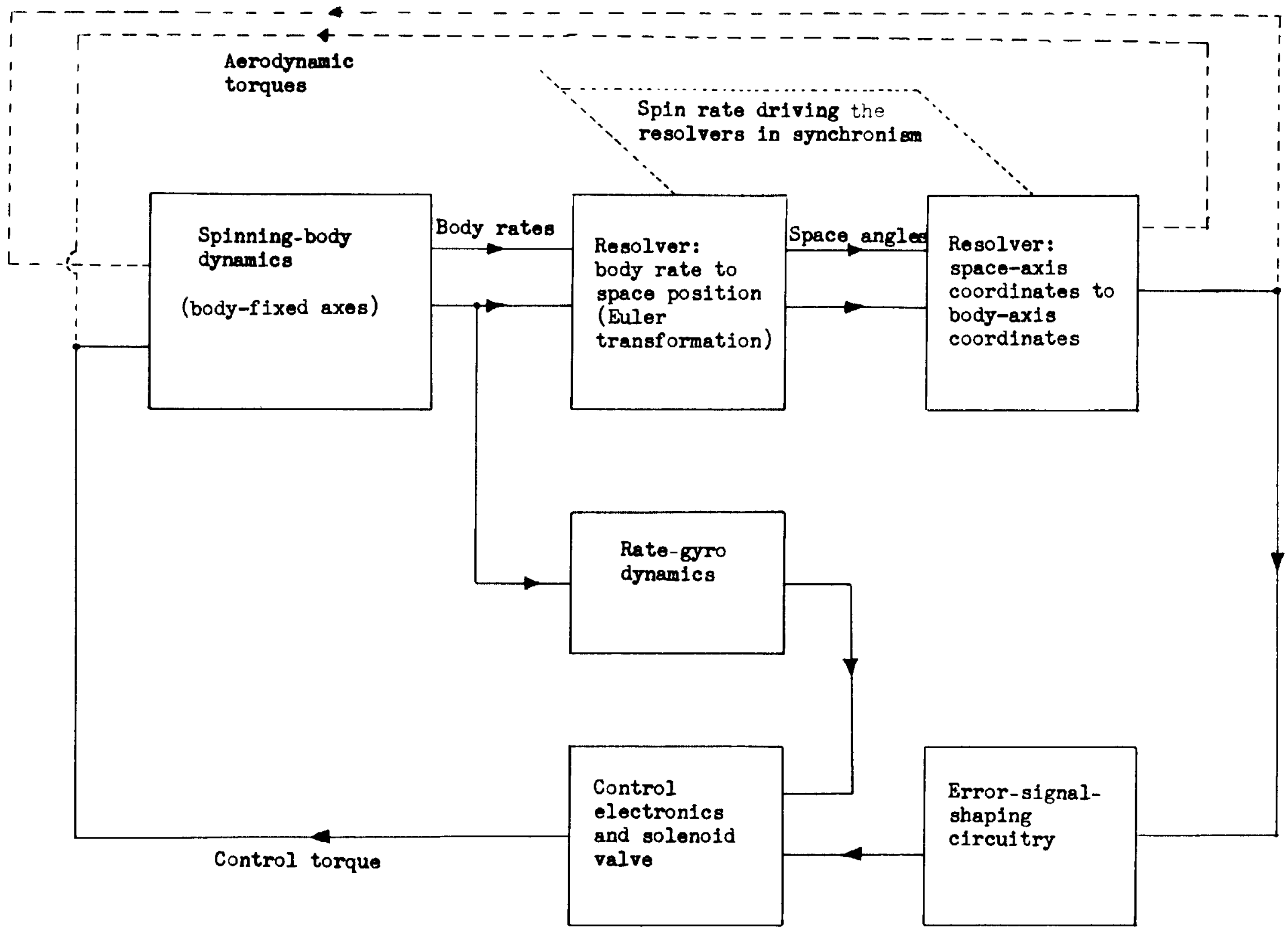

Figure 6.- Generalized simulation block diagram.

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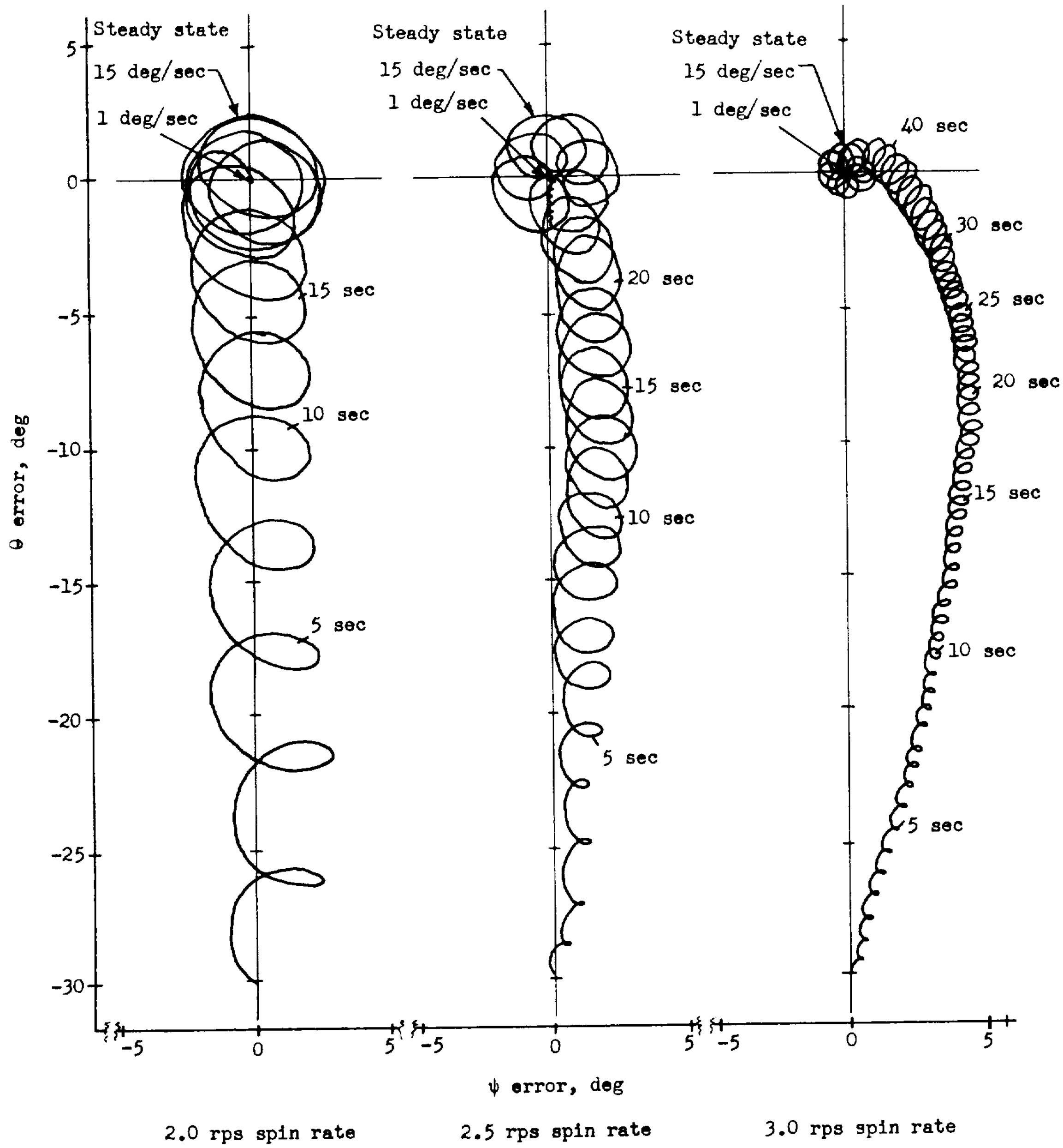

Figure 7.- Typical computer results for horizontal-control system with azimuth control, on-off signal mixing, and a damping signal switched from 15 deg/sec threshold to 1 deg/sec threshold at 90 seconds after control initiation.

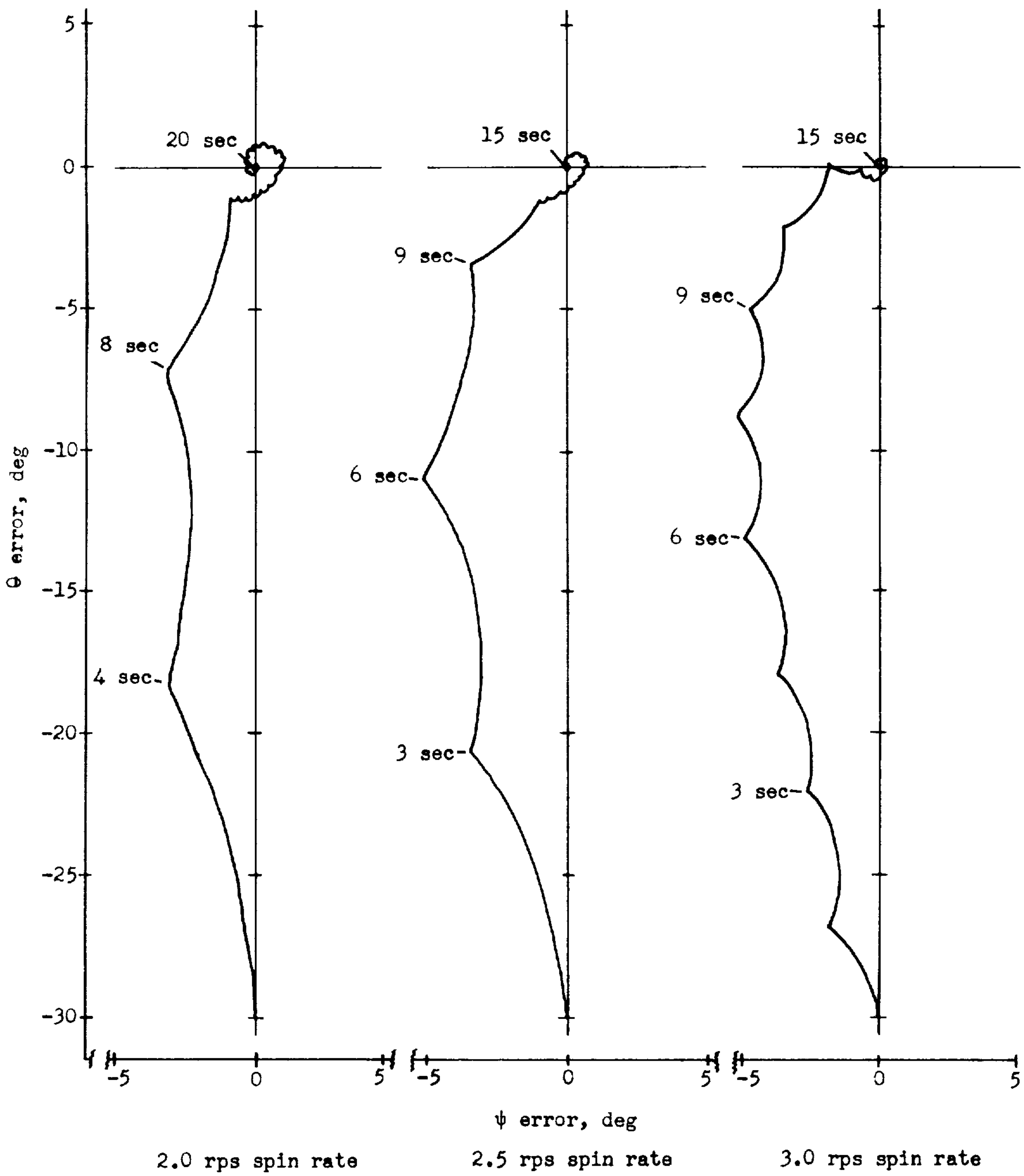

Figure 8.- Typical computer results for vertical-control system with analog-signal mixing and gain ratio of 5.33 deg/sec/deg.

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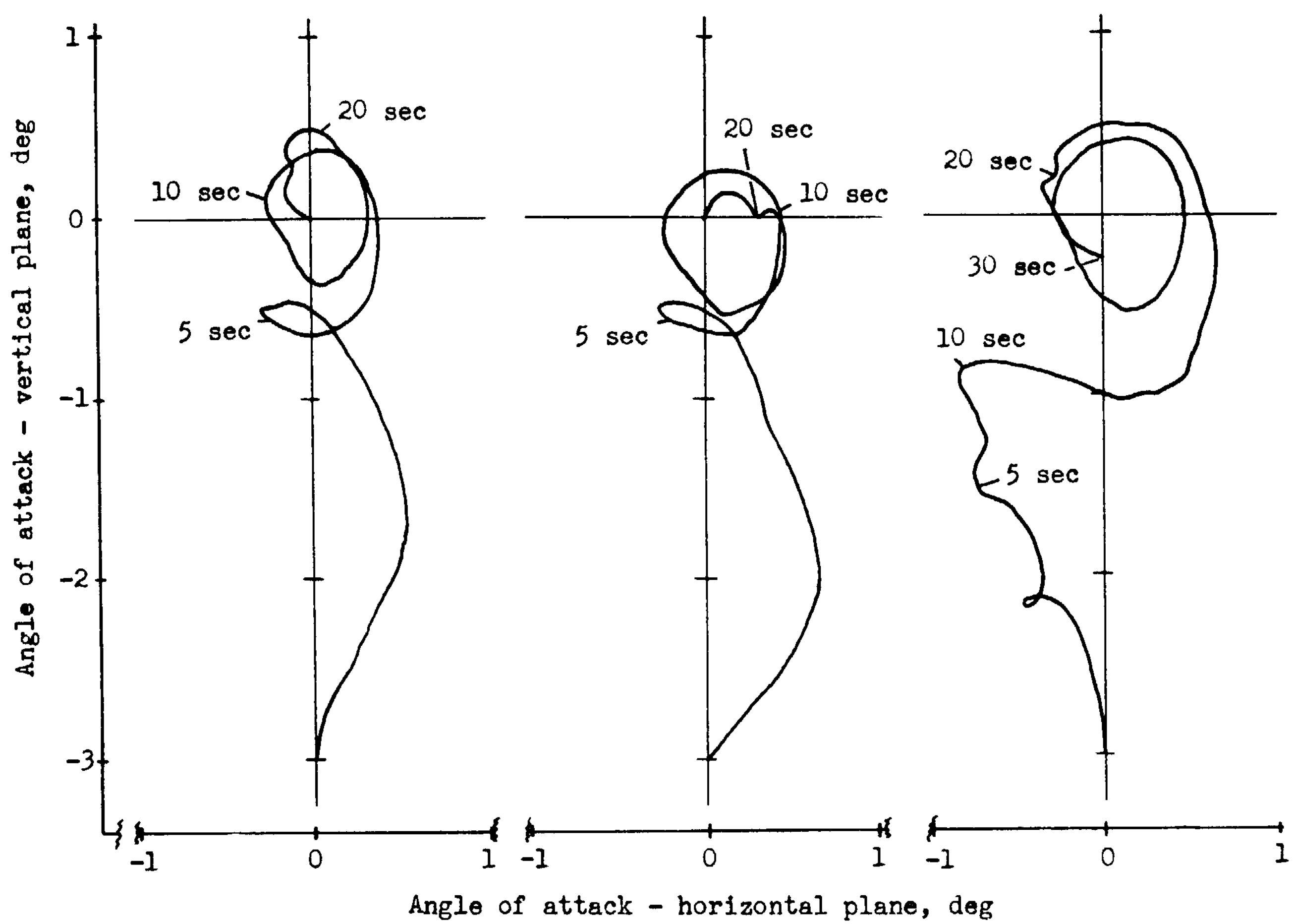

2.0 rps spin rate   2.5 rps spin rate   3.0 rps spin rate

Figure 9.- Typical computer results for angle-of-attack control system with analog-signal mixing, variation of angle-of-attack signal gain with dynamic pressure, and varying aerodynamic moments.

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